IJSPT

ORIGINAL RESEARCH

SPATIOTEMPORAL PARAMETERS OF ADOLESCENT GAIT WHEN PERFORMING A VISUOSPATIAL MEMORY TASK

Leah M. Lowe, PhD, DPT[1]
Yevgeniya Gokun, MS[2]
David K Williams, MPH, PhD[2,3]
Charlotte Yates, PhD, PT[1,3]

ABSTRACT

Background: Accurate assessment of recovery following mild traumatic brain injury in adolescents can be difficult. When compared to single-task models, dual-task models that combine cognitive and motor demands may more accurately identify residual deficits that manifest during daily life and athletic play in adolescents with concussion. Previous studies have examined gait changes during a concurrent auditory task, or cognitive task.

Purpose: The purpose of this study was to collect and present data from a sample of healthy 14-18 year old male and female athletes on spatiotemporal parameters of gait for walking with and without a concurrent visuospatial memory task presented on a hand-held tablet.

Study Design: A two-way repeated measures study of spatiotemporal gait parameters in a cross-sectional convenience sample of adolescent subjects participating in high school athletics.

Methods: Subjects comprised a total of 178 adolescent athletes (128 males; 50 females) ages 14-18 years old at six area high schools. Subjects were instructed to walk "how you normally do" on the GAITRite® portable gait analysis walkway for three undivided and three divided attention trials performing a visuospatial memory task on a hand-held tablet.

Results: Significant differences ($p < 0.0001$) were present between males and females during typical gait in each of the measured parameters except step length ($p = 0.0715$). Female participants walked with a significantly faster gait velocity (by 0.21 m/s) than male participants ($p < 0.0001$). The females spent a significantly smaller (-2.27%) percent of the gait cycle in double limb support ($p < 0.0001$) and a significantly greater (+1.10%) percent of the gait cycle in single limb support ($p < 0.0001$) than did the males. Both groups experienced a similar, dual-task cost during the divided attention trials ($p < 0.0001$) for each of the four gait parameters. Previous studies have shown that adults decrease their gait velocity by approximately 33% when performing a task on a hand-held device. The current study revealed that adolescents decreased their gait velocity by 8-9% by shortening their step length by 7.4 centimeters ($p < 0.0001$), increased the percent of the gait cycle spent in double limb support (2.73%, $p < 0.0001$) and decreased the percent of the gait cycle spent in single limb support (1.38%, $p < 0.0001$) during the dual-task.

Conclusion: These data provide preliminary reference values specific to the adolescent population for the dual-task cost during a visuospatial memory task. More research is needed to determine the dual-task cost during a visuospatial memory task for adolescents with concussion.

Level of Evidence: 2b

Keywords: adolescent, concussion, dual-task, gait, movement system

[1] Department of Physical Therapy, University of Central Arkansas, Conway, AR, USA
[2] Department of Biostatistics, University of Arkansas for Medical Sciences, Little Rock, AR, USA
[3] Center for Translational Neuroscience, University of Arkansas for Medical Sciences, Little Rock, AR, USA

Conflict of Interest: The authors have no conflict of interest to disclose.

Funding: This study was supported by NIGMS IDeA Program award P30 GM110702 through the Center for Translational Neuroscience at the University of Arkansas for Medical Sciences.

Acknowledgements: We thank the coaches, staff, and athletes from the following schools: Sylvan Hills High School in North Little Rock, AR; Joe T. Robinson High School in Little Rock, AR; Little Rock Christian Academy in Little Rock, AR; Warren High School in Warren, AR; Drew Central High School in Monticello, AR; and Hamburg High School in Hamburg, AR. We acknowledge Morgan Crowder, Taylor Guinn, Lauren Hart, Jaden Hoth, Emily Jones, Lauren Cook, Kylie Furman, and Timia Watson for their assistance with data collection.

CORRESPONDING AUTHOR

Dr. Leah Lowe, Department of Physical Therapy, University of Central Arkansas, Physical Therapy Center, Suite 300, 201 Donaghey Avenue, Conway, Arkansas 72035
Tel: 1-501-450-5545
E-mail: llowe@uca.edu

INTRODUCTION

Concussion, classified as a mild traumatic brain injury, is a functional brain disturbance that may be caused by a direct or indirect force transmitted to the head.[1] Concussion is the most common head injury in athletics, and the incidence of emergency room visits for sport-related concussion in 14-19 year olds has increased by more than 200% over a 10 year span (1997-2007).[2-4] Sport-related concussion (SRC) represents as many as 3.8 million reported non-fatal traumatic brain injuries each year leading the Center for Disease Control to conclude that this type of injury has reached an epidemic level.[1,5-9]

Return to activity decisions, including return to athletic play, following concussion in adolescents can be complicated, as clinical presentation varies greatly across individuals. Since the consequences of concussion can be both acute and chronic, the need for objective, quantifiable clinical measures by which to evaluate full recovery from the injury is ongoing.[1,5,10] Currently, the recommended assessment battery for individuals suspected to have SRC consists of neurocognitive assessment, symptom checklists, and a neurological assessment.[10] Though cognition, oculomotor function, gross sensorimotor, coordination, gait, vestibular function, and balance are all components of the recommended neurological assessment, these tests may not measure changes in functional mobility with return to everyday activities, changes that are likely exacerbated by the cognitive and motor demands of higher level athletic participation.[10-12]

When compared to single-task models, dual-task models that combine cognitive and motor demands may more accurately identify deficits that manifest during daily life as well as athletic play.[13-17] If incorporated into post-concussion evaluation, these models could contribute additional, helpful information related to recovery. Fabri et al.[13] report that by comparing dual-task conditions to single-task conditions, a poorer performance on the dual-task can suggest that the individual has a reduced capacity to perform at baseline. This reduction in performance during a dual-task condition is the dual-task cost (DTC). The protocols for dual-task gait activities used in the literature vary, but two tasks, in particular, are often paired with gait and studied for DTC: 1) auditory Stroop Task variations or 2) modified Mental State Exam (MSE).[16] The audio variation of the Stroop Task asks subjects to correctly identify the pitch (high or low) of the spoken words, "high" or "low", despite whether the actual pitch and word are paired congruently.[16] The Single Auditory Stroop (SAS) task plays the word one time per trial while the Multiple Auditory Stroop (MAS) task plays the words multiple times per trial.[16,18-20] The MSE includes simple mental tasks that include spelling five-letter words backward, subtracting consecutively by 7's from a randomly selected two-digit number, and reciting the months of the year in reverse order from a randomly selected month.[14,20-22] Dual-task studies, specifically using these attention tasks in combination with a gait activity, have found that adolescents and adults with both acute and chronic concussion have been shown to have decreased gait balance control demonstrating significantly altered DTC.[12,14,18-25]

Howell et al.[18] reported that, when walking while completing the auditory Stroop Task, gait balance control deficits in adolescents were greater than in young adults both initially and throughout the two months post-injury. Greater deficits in the adolescent population could be related to the continuing, yet incomplete, cognitive development and maturation of critical systems for postural control as well as the ability to adapt locomotor strategies to environmental demands.[26-27] Furthermore, evidence suggests that, in adolescents, gait balance control may be affected by the complexity of the cognitive task, indicating that dual-task models employing more complex scenarios may be more sensitive to subtle deficits impeding complete recovery.[19-20]

Regarding additional spatiotemporal parameters of gait, Parker et al.[21] found that college-aged subjects completing the MSE while walking walked slower up to 28 days following a concussion and with a shorter stride length up to 14 days after the injury. Howell et al.[19] reported that when walking with a concurrent auditory Stroop task, concussed adolescents and their controls both walked with decreased velocity; however, the adolescents with concussion demonstrated a significantly greater DTC in gait velocity than the age-matched controls. While auditory stimuli processing of varying complexity during everyday activity as well as athletic play is imperative, dual-task assessment models combining a dynamic movement and a visuospatial memory task could reveal additional helpful information regarding the DTC in individuals who rely heavily on visual input.[26] Martini et al.[24] found that individuals with a history of concussion (mean of 6.3 years post-concussion) adopted a more conservative gait strategy than control subjects by increasing the time spent in double limb support (DLS) and decreasing the time spent in single limb support (SLS) during dual-task walking with a visuospatial memory task, the Brooks' Spatial Memory Task. During the combined gait and Brooks' Spatial Memory trials, subjects in Martini's study who had been shown a 4x4 grid of numbers verbally recited from memory the spatial location of the numbers while walking.[24] Though their visuospatial memory was tested, their visual field was open and the subjects had access to the broader environment. Currently, no studies exist examining the effect of a visuospatial memory task during gait in adolescents with concussion. While the literature supports the expectation of greater DTC to a variety of spatiotemporal gait parameters in adults with acute and chronic concussion, more information is needed related to the DTC in adolescents with concussion.

In a 2017 Howell et al.,[28] provided important insight into normative values for healthy (non-concussed), collegiate athletes during single-task and dual-task gait. During the dual-task component of this study, the athletes completed the MSE, by verbally responding to prompts while walking.[28] Additionally, data in healthy young adults walking while completing a cognitive task on a smart phone is available.[29-30] While recent, normative spatiotemporal single-task gait data for healthy adolescents is available,[31] baseline data for healthy adolescents combining a motor and cognitive (visuospatial memory) task with altered visual attention (use of a tablet or phone) during gait is not available, despite the everyday nature of this type of task. Tasks that involve manipulation of an object with visual attention on the object rather than the broader environment are commonplace both in daily activity (i.e. texting while walking) and in athletic play (i.e. manipulating a ball with visual focus on the closest opponent while advancing down the court or field). An altered, or larger than expected, DTC during a combined motor and cognitive task post-concussion could pose a risk to adolescents returning to daily activity and especially athletic play with expectations to combine numerous dynamic movement requirements with diverse cognitive processes and environments. However, because many adolescents present for concussion management without baseline measures, values for clinical comparison and decision-making specific to the adolescent population are needed.

Therefore, the purpose of this study was to collect and present data from a sample of healthy 14-18 year old male and female athletes on spatiotemporal parameters of gait for walking with and without a concurrent visuospatial memory task presented on a hand-held tablet. The investigators hypothesized that, during the dual-task efforts, all subjects would experience a significant DTC. The investigators also hypothesized no significant differences in the DTC between males and females, but anticipated a smaller DTC to gait velocity than what is reported for adults.

METHODS

Participants

A convenience sample of 178 male (n = 128) and female (n = 50) athletes, between the ages of 14-18 years old, were recruited from three area high school football programs and three area female sports programs (primarily soccer), representing six separate school districts. All data collection was performed in the athletes' school setting. Participant demographics are represented in Table 1. Participants were excluded if they did not have a pre-participation sports form on file with the school they attended or if they had a diagnosed concussion within six months prior to data collection. The Institutional Review Board at the University of Arkansas for Medical Sciences approved the study. All participants and guardians provided written informed consent to participate in the study.

Protocol

Gait parameters were assessed by instructing the participants (n = 178) to walk at a self-selected speed on the GAITRite® (CIR Systems, Inc.; Franklin, NJ) portable gait analysis walkway for three, undivided

Table 1. *Participant demographics by age, race, and ethnicity.*

	Male	Female
Age		
14 years	n=4	n=5
15 years	n=43	n=14
16 years	n=39	n=12
17 years	n=40	n=11
18 years	n=2	n=8
Race		
Caucasian	n=62	n=20
African American	n=57	n=13
Two or More	n=4	n=5
Not Selected	n=5	n=12
Ethnicity		
Hispanic	n=0	n=14
Non-Hispanic	n=123	n=25
Not Selected	n=5	n=11

attention trials and three, divided attention trials. During each divided attention trial, a visuospatial memory task was given to the subjects to complete on a tablet (2016 *Microsoft Surface Pro 11.5" x 7.9" x 0.33"; Taiwan, China*) while walking. Participants used a tablet rather than their own cell phones to achieve novelty and require attention to the device. The task (Pattern Memory by ProProfs.com available at www.memory-improvement-tips.com), similar to the visuospatial memory tasks commonly included in the neurocognitive testing used in concussion management, consisted of a one-second period of time to view a pattern of shapes arranged spatially on the tablet screen. After this time period, the shapes disappeared. The subjects then had to place the shapes in the original position relying upon visuospatial working memory. Subjects who typically wear corrective eyewear (e.g. glasses or contact lens) wore them during the assessment. All subjects performed this task in the same manner with three practice attempts to learn the task in static stance and data collection during gait beginning at level four of the task. Additionally, the subjects initiated the task 2.5 meters prior to stepping onto the pathway to allow the task to continue throughout the entirety of the sensor pathway. Investigators monitored each trial to ensure that the participant was actively completing the task throughout the data recording time period. If the participant failed at the task, causing the game to discontinue during a trial, that trial was repeated to ensure that the participant was actively completing the task throughout.

The GAITRite® portable gait analysis walkway and corresponding GAITRite® software recorded temporal and spatial parameters. Prior to each participant's trials, investigators entered leg length data. Leg length was measured as the distance from greater trochanter to floor for each leg. For the purposes of this study, parameters that were captured by the GAITRite® include: gait velocity (cm/s); step length (cm); DLS, defined as the percent of the gait cycle (%GC) when both feet are on the ground; and SLS, defined as the %GC weight bearing through a single limb. The walkway is 5.186 meters long and embedded with sensors recording footfall pressures at 80 Hz, which allows calculation of temporal and spatial markers of gait. The software averages the three gait trials under each walk condition providing means for each parameter. The GAITRite® system has been shown to be a reliable and valid measure of gait for healthy individuals.[32]

Statistical Methods

Descriptive analysis, including means and standard deviations was used to summarize all participant data. Normalized velocity was calculated by the GAITRite® system by dividing the gait velocity captured by the GAITRite® (cm/s) by the participant's leg length (cm) and then converting the value to meters per second (m/s) for reporting.[27,32-33] Normality was tested and assumed for all measured gait parameters. A two-way repeated measure analyses of variance (ANOVA) was conducted to explore the impact of walk status (i.e. walking with or without the dual task condition) and sex on spatiotemporal gait parameters of velocity, step length, % GC in DLS, and % GS in SLS. This analysis was conducted using

SAS PROC MIXED with adjustments using Tukey's post hoc method for the pairwise comparisons between walk status and sex for each gait parameter. Data analysis was conducted using SAS v9.4 (SAS Institute; Cary, NC; www.sas.com). The level of statistical significance was set at $p < 0.05$.

RESULTS

The means and standard deviations for single and dual task efforts along with the average DTC and standard deviations are summarized in Table 2. The interaction effect for walk status and sex was not significant for any of the four gait parameters tested ($p > 0.05$) and therefore, the DTC was not statistically significantly different between males and females for any of the tested gait parameters.

A statistically significant main effect for sex was found for all gait parameters except step length. Male and female adolescents, when instructed to "walk as you normally do," did not walk with a significantly different step length ($p = 0.0715$). However, on average, female participants did walk with significantly faster gait velocity (by 0.21 m/s) than male participants ($p < 0.0001$). Additionally, on average, the females spent a significantly smaller %GC, -2.27%, in DLS ($p < 0.0001$) and a significantly greater %GC, +1.10%, in SLS ($p < 0.0001$) than did the males. Figure 1 shows the mean plots with 95% confidence intervals of each gait parameter with walk status by sex.

Also, a statistically significant main effect occurred for walk status and thus, male and female participants both experienced a significant DTC when walking with a visuospatial memory task and altered visual attention. The male and female participants both significantly slowed their gait velocity by an average of 0.21m/s and shortened their step length by an average of 7.4 centimeters ($p < 0.0001$) during the dual-task condition. Also, both males and females significantly increased the %GC spent in DLS (on average by 2.73%, $p < 0.0001$) and on average, decreased the %GC spent in SLS (on average by 1.38%, $p < 0.0001$) during the dual-task condition.

DISCUSSION

This research on healthy adolescents builds upon the growing evidence for implementation of dual-task conditions in individuals to more specifically isolate deficits, which could place them at an increased risk for injury with return to normal activity after an injury. The dual-task protocol used in this study employs typical functional movement and motor demands in conjunction with a visuospatial memory task and altered visual attention, a combination which mimics the dynamic and dual-task nature of the real world more closely than static, single-task assessments commonly utilized in concussion assessment.

Gait velocity is the most commonly reported gait parameter used for outcomes involving gait analysis. The single-task gait velocity in this sample of adolescent males (n = 128) and females (n = 50) is consistent with the recently published data by McKay et al.[31] Also consistent with previous studies, the results from this study indicate the presence of

Table 2. *The means and standard deviations of the gait parameters when subjects walked without a concurrent visual-cognitive task (Single Task) and with a concurrent visual-cognitive task (Dual Task). The means and standard deviations for the dual-task cost for each parameter (DTC).*

	Single Task		Dual Task		DTC	
Parameter	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**
Velocity (m/s)	1.236 (0.163)	1.449 (0.199)	1.030 (0.185)	1.232 (0.196)	-0.205 * (0.140)	-0.217 * (0.113)
Step length (cm)	68.031 (6.779)	65.483 (6.021)	60.073 (7.858)	58.650 (5.885)	-7.958 * (5.046)	-6.833 * (3.777)
% in DLS	29.077 (2.631)	26.922 (2.648)	31.92 (3.461)	29.542 (3.085)	+2.847% * (2.753)	+2.620% * (1.783)
% in SLS	35.390 (1.504)	36.522 (1.352)	34.05 (1.901)	35.112 (1.549)	-1.343% * (1.665)	-1.410% * (1.129)

*Statistically significant DTC at p<0.0001

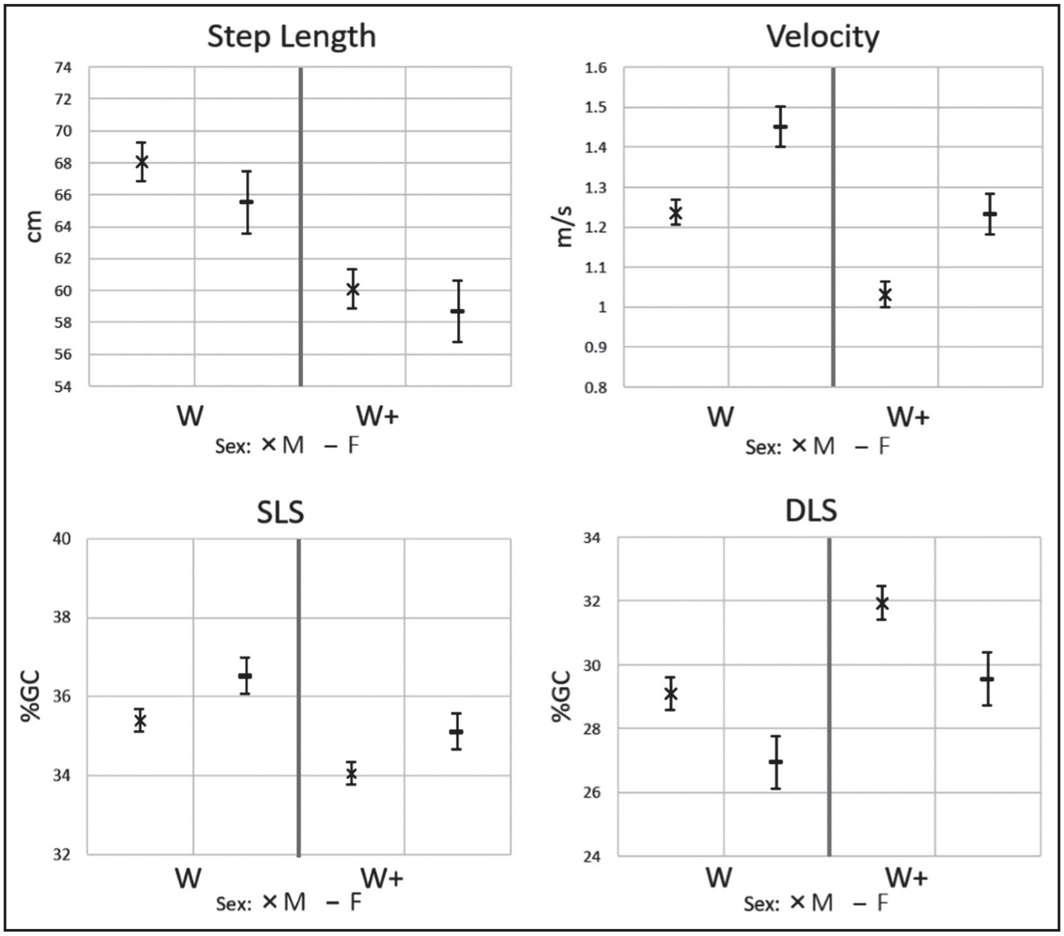

Figure 1. *Mean plots with 95% confidence intervals of each gait parameter with walk status by sex.*

a significant DTC to spatiotemporal gait parameters when gait is combined with an additional task.[14,21-22] However, unlike a smaller sample of adolescents who walked with a concurrent auditory task, the athletes in this study walking with a visuospatial memory task and altered visual attention, as expected, significantly decreased their step length to adopt a more conservative gait strategy.[19]

The present findings also demonstrate that, like adults in a non-concussed control group, the healthy adolescents in our study demonstrated a more conservative gait strategy during a dual-task walking condition by decreasing their gait velocity, increasing the time spent in double limb support during the gait cycle, and decreasing the time spent in single limb support during the gait cycle.[22] However, contrary to literature regarding walking with visual attention on a cell/smart phone in adults, the adolescents in this study decreased their gait velocity by approximately 8-9%, while adults typically decreased their gait velocity by approximately 33%.[29-30] This result may speak to the commonality of this type of multi-tasking in the adolescent population and to its ability to more closely mimic real activities in their daily life.

The evidence has shown that collegiate and professional athletes have been found to be at an increased risk for subsequent musculoskeletal injury following concussion as far as one year out, with authors suggesting that continued deficits in neuromotor control may be implicated.[34-35] These findings suggest that athletes who return to play, even upon successful completion of a graded exertion plan, may be playing with altered, less efficient, and potentially dangerous movement patterns that could contribute to further injury including subsequent concussion or orthopedic injury to the limbs or spine. The evidence has also established that adolescents and adults post-concussion demonstrate decreased balance control during gait, a natural and automatic motor task.[12,14,18-24] In 2011, Martini et al.[24] further documented that young adults (mean age of 21 years old) who, on average, were 6.32 years out from their concussion continued to demonstrate more conservative strategies during gait than the non-concussed controls. Those combined findings indicate that adults who sustained one or more concussions during their adolescent years could still be experiencing functional movement disturbances even into adulthood. Of future importance to investigate, the costs associated with dual-task efforts involving a visuospatial memory task and altered visual attention in adolescents with SRC could also be amplified both acutely and chronically as seen with previously studied dual task conditions. By using the protocol described in the current study to assess concussed adolescents, researchers, using these baseline data, may have an additional tool to better detect and isolate persistent movement impairments in this population.

LIMITATIONS

These data were generated using a sample of convenience in a group of adolescents with a narrow age range, which may lend to decreased generalizability of the findings. Further research with a greater number of participants, especially more females, across a wider age range would contribute a more robust data set. Also, data collection was performed in the athletes' school environment. While this provided a more natural setting in which to observe normal movement, additional distractions could not be fully minimized. Additionally, data collection was performed using an expensive piece of equipment, not readily available to most clinicians. Future research comparing data obtained using the same visuospatial memory task during gait, but through utilization of more traditional and clinically feasible tools (e.g. 10 Meter Walk Test) would be helpful in providing useful data to more clinicians in a variety of settings. Finally, the complexity of the visuospatial memory task was not customized to the subject's individual cognitive or motor capacities. Therefore, the attention requirements could have been variable for each participant. Future studies could assign the complexity of the task based upon a baseline cognitive assessment.

CONCLUSIONS

The results of the current study provide novel research evidence regarding the DTC associated with a combination of motor, cognitive, and visual demands during gait in healthy adolescent athletes. This task combination required utilization of the visual system upon which these still developing individuals heavily rely both on and off the field. Even in healthy adolescent athletes, the DTC significantly affected both their approach to and performance of motor demands. These data may provide clinicians treating adolescents with useful clinical comparison values. More research is needed to determine if this testing protocol, in combination with the presented clinical comparison values, can reveal significantly altered DTC in concussed adolescents and ultimately guide rehabilitation decisions as well as safe return to play for these individuals.

REFERENCES

1. Halstead ME, Walter KD; Council on sports medicine and fitness. American Academy of Pediatrics. Clinical report—sport related concussion in children and adolescents. *Pediatrics.* 2010;126(3):597-615.
2. Guskiewicz KM, Weaver NL, Padua DA, et al. Epidemiology of concussion in collegiate and high school football players. *Am J Sports Med.* 2000;28(5):643-650.
3. Bakhos LL, Lockhart GR, Myers R. et al. Emergency department visits for concussion in young child athletes. *Pediatrics*. 2010;126:550-556.
4. De Beaumont L, Lassonde M, Leclerc S, et al. Long-term and cumulative effects of sports concussion on motor cortex inhibition. *Neurosurgery.* 2007;61:329-337.
5. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil.* 2006;21:375-378.
6. Giza CC, Kutcher JS, Ashwal S. et al. Summary of evidence-based guideline update: evaluation and management of concussion in sports. *Neurology.* 2013;80:2250-2257.
7. Scorza, KA. Raleigh MA, O'Connor FG. Current concepts in concussion: evaluation and management. *Am Fam Physician*. 2012;85(2):123-132.
8. Faul M, Xu L, Wald M, et al. Traumatic brain injury in the United States: emergency department visits, hospitalizations, and deaths, 2002-2006. Atlanta, GA: Centers for Disease Control and Prevention. National Center for Injury Prevention and Control.

9. Broglio SP, Cantu RC, Guskiewicz KA, et al. National Athletic Trainers' Association position statement: management of sport concussion. *J Athl Train.* 2014;49(2):245-265.
10. McCrory P, Meeuwisse WH, Dvorak J, et al. Consensus statement on concussion in sport: the 5th International Conference on Concussion in Sport held in Berlin, October 2016. *Br J Sports Med*. 2018;51:838-847.
11. Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the concussion assessment battery. *Neurosurgery.* 2007;60:1050-1058.
12. Howell DR, Osternig LR, Chou LS. Return to activity after concussion affects dual-task gait balance control recovery. *Med Sci Sport Exer.* 2015;47(4): 673-680.
13. Fabri TL, Wilson KE, Holland N, et al. Using a dual-task protocol to investigate motor and cognitive performance in healthy children and youth. *Gait & Posture*. 2017;54: 154-159.
14. Parker TM, Osternig LR, Lee HJ, et al. The effect of divided attention on gait stability following concussion. *Clin Biomech.* 2005;20:389-395.
15. Weerdesteyn V, Schillings AM, van Galen GP, Duysens J. Distraction affects the performance of obstacle avoidance during walking. *J Motor Behav.* 2003;35(1):53-63.
16. Grants L, Powell B, Gessel C, Hiser F, Hassen A. Gait deficits under dual-task conditions in the concussed adolescent and young athlete population: a systematic review. *Int J Sports Phys Ther.* 2017;12(7):1011-1022.
17. Parker TM, Osternig LR, van Donkelaar P, Chou LS. Recovery of cognitive and dynamic motor function following concussion. *Br J Sports Med.* 2007;41: 868-873.
18. Howell DR, Osternig LR, Chou LS. Adolescents demonstrate greater gait balance control deficits after concussion than young adults. *Am J Sport Med.* 2014;43(3):625-632.
19. Howell DR, Osternig LR, Chou LS. Dual-task effect on gait balance control in adolescents with concussion. *Arch Phys Med Rehabil.* 2013;94:1513-1520.
20. Howell DR, Osternig LR, Koester MC, et al. The effect of cognitive task complexity on gait stability in adolescents following concussion. *Exp Brain Res.* 2014;232: 1773-1782.
21. Parker TM, Osternig LR, van Donkelaar P, et al. Gait stability following concussion. *Med Sci Sport Exer.* 2006;38(6):1032-1040.
22. Catena RD, van Donkelaar P, Chou LS. Altered balance control following concussion is better detected with an attention test during gait. *Gait & Posture.* 2007;25:406-411.
23. Ruffieux J, Keller M, Lauber B, et al. Changes in standing and walking performance under dual-task conditions across the lifespan. *Sports Medicine.* 2015;45:1739-1758.
24. Martini DN, Sabin MJ, DePesa SA, et al. The chronic effects of concussion on gait. *Arch Phys Med Rehabil.* 2011;92:585-590.
25. Catena RD, van Donkelaar P, Chou LS. The effects of attention capacity on dynamic balance control following concussion. Journal of NeuroEngineering and Rehabilitation. 2011; 8: 1-8.
26. Catena RD, van Donkelaar, Chou LS. Cognitive task effects on gait stability following concussion. *Exp Brain Res.* 2007;176:23-31.
27. Abbruzzese LD, Rao AK, Bellows R, et al. Effects of manual task complexity on gait parameters in school-aged children and adults. *Gait & Posture.* 2014;40:658-663.
28. Howell DR, Oldham JR, DiFabio M, et al. Single-task and dual-task gait among collegiate athletes of different sport classifications: implications for concussion management. *JAB.* 2017;33:24-31.
29. Lamberg EM, Muratori LM. Cell phones change the way we walk. *Gait & Posture.* 2012;35(4):688-690.
30. Jeon SY, Kim CR, Son SH, et al. Changes in gait pattern during multitask using smartphones. *Work.* 2016;53:241-247.
31. McKay MJ, Baldwin JN, Ferreira P, et al. Spatiotemporal and plantar pressure patterns of 1000 healthy individuals aged 3-101 years. *Gait & Posture.* 2017;58:78-87.
32. Webster KE, Wittwer JE, Feller JA. Validity of the GAITRite walkway system for the measurement of averaged and individual step parameters of gait. *Gait & Posture.* 2005;22:317-321.
33. Hof AL. Scaling gait data to body size. *Gait & Posture.* 1996;4:222-223.
34. Lynall RC, Mauntel TC, Padua DA, et al. Acute lower extremity injury rates increase following concussion in college athletes. *Med Sci Sports Exerc.* 2015;47(12):2487-2492.
35. Pietrosimone B, Golightly YM, Mihalik JP, Guskiewicz KM. Concussion frequency associates with musculoskeletal injury in retired NFL players. *Med Sci Sports Exerc.* 2015; 47(11): 2366-2372.